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# **A comparison of modelled and real-life driving profiles for the simulation of railway vehicle operation**

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# **A comparison of modelled and real-life driving profiles for the simulation of railway vehicle operation**

A key factor in determining the performance of a railway system is the speed profile of the trains within the network. There can be significant variation in this speed profile for identical trains on identical routes, depending on how the train is driven. A better understanding and control of speed profiles can therefore offer significant potential for improvements in the performance of railway systems. This paper develops a model to allow the variability of real-life driving profiles of railway vehicles to be quantitatively described and predicted, in order to better account for the effects on the speed profile of the train and hence the performance of the railway network as a whole. The model is validated against data from the Tyne and Wear Metro, and replicates the measured data to a good degree of accuracy.

Keywords: railway system, simulation, driving style, driving profile, driver behaviour, driving strategy, speed profile, Tyne and Wear Metro

## **Nomenclature**

$D$	-	Deceleration rate ( $\text{m s}^{-2}$ )
$Vb1$	-	Brake step 1 control parameter
$Vb2$	-	Brake step 2 control parameter
$Vb3$	-	Brake step 3 control parameter
$VbFS$	-	Full service brake step control parameter
$Vc$	-	Coasting speed ( $\text{m s}^{-1}$ )
$Vo$	-	Line speed limit ( $\text{m s}^{-1}$ )
$Vt$	-	Target speed ( $\text{m s}^{-1}$ )
$\mu$	-	Mean
$\sigma$	-	Standard deviation

## **1. Introduction**

Railways are large and complex systems, consisting of many diverse and interdependent elements (Schmid, 2012). As such, simulation provides the only practical way of

investigating the performance of the system under different conditions. Many potential measures of performance can be defined; capacity, journey time and energy consumption are some examples that are particularly relevant to this paper. System-level analysis must however take account of all of the interactions within the system (González-Gil et al., 2014), and there has been continuous development of computer simulations of increasing complexity over the last sixty years in order to meet this need and effectively plan future investment in railway systems (Hargreaves, 1974; Goodman et al., 1998; Jacob et al., 2013).

The speed-time profile of the trains within the railway is central to such simulations, and will depend on the physical characteristics of the trains and infrastructure, the operational constraints of timetable and signalling, and driver behaviour. The performance of a train is characterised by the relationship between speed and tractive or braking effort (force), and for a particular train this depends on the design of the control system as well as the rating of the traction equipment. There are four different operational phases of the train within the speed profile: acceleration, cruising, coasting and braking. The driving profile is defined in this paper as a quantitative measure of driver behaviour: the actions of the driver in operating the controls to achieve a particular level of tractive or braking effort, in order to meet the target speed profile for the operational phase in question. The driving strategy is defined as the choices made in determining the driving profile.

The principal aim of this paper is therefore the development from first principles of a simple simulation model that can replicate different real measured speed-time profiles by calibrating simulation input parameters that describe the driving profile. Precedent for this approach can be found in the literature: De Fabris et al. (2010) used measured speed profile data to calibrate a stochastic simulation model of train

movement, although the results were purely empirical. De Martinis et al. (2013) used a similar approach to calibrate a deterministic simulation model that investigated potential energy savings through coasting. Bešinović (2013) used track occupation data to derive speed profiles, which were then used to calibrate a model of the train characteristics.

The outline methodology proposed for this paper combines and develops these ideas, with an analytical model of both the driving profile and the traction and control systems of the train. It is proposed that the variation in input parameters when the model is used to replicate several different measured profiles can then be used as a proxy to describe the stochastic variation in driver behaviour for the measured profiles of a given route and train. The Tyne and Wear Metro in Newcastle is used as a case study, to provide real-life data for validation of the model, although the methodology itself is equally applicable to other railway systems and train designs.

The structure of the paper is as follows: Section 2 examines each of the four operational phases identified above in more detail, to provide more information about the necessity and characteristics of each, and to support the development of a driver model. Section 3 contains a brief overview of the Tyne and Wear Metro and Section 4 comprises the modelling methodology. Sections 5-7 summarise the results of the model calibration and validation, together with a discussion of the results and the conclusions of the paper.

## **2. Operational phases**

### ***2.1 Acceleration***

In most situations when accelerating, the maximum tractive effort available is demanded from the traction system until the train reaches either the speed limit for the line or a point where deceleration is required to meet a speed restriction or stop further

ahead. The maximum tractive effort is only available at lower speeds: once the speed is sufficient for the power limit of traction equipment to be reached, further increases in speed will result in a reduction in available force. There are several reasons why a tractive effort lower than the maximum may be demanded however:

- Adhesion - this is defined as: the ratio of the longitudinal force actually applied at the wheel/rail contact (in this case tractive effort) to the vertical reaction force (instantaneous axle load on powered wheelsets), and can be considered equal to the coefficient of friction between wheel and rail at its limiting value. The design value of assumed adhesion coefficient for maximum tractive effort to be developed varies between different trains: typically 10-15% for multiple units and 20-30% for locomotives, although there are examples outside these ranges. The actual adhesion available strongly depends on the conditions however, and may vary from over 30% on clean, dry rails to less than 5% on damp rails contaminated by leaf-fall (*Adhesion Working Group, 2004*). In such conditions, the tractive effort demand must be reduced to prevent wheelspin; this may be done by the driver or automatically by the train's Wheel Slip Protection (WSP) system.
- Motor temperature - if the continuous rating of electric traction motors is exceeded for a significant length of time, the tractive effort demand must be reduced to prevent overheating. Examples include heavy trains accelerating up long gradients, or a train that also uses the motors for dynamic braking going through many start/stop cycles in a short period of time.
- In-train forces - heavy locomotive-hauled trains may also require different driving strategies while accelerating in order to minimise in-train forces, as the maximum tractive effort combined with forces due to track gradients and

transient dynamic effects can lead to a broken coupler between vehicles in the train.

- Jerk level - the rate at which the actual tractive effort ramps up to meet the maximum demand may be limited. This reduction in jerk (the rate of change of acceleration) may be to improve passenger comfort and minimise the chances of injury, or to reduce excess diesel engine emissions associated with rapid changes in power/speed levels.

The driver's controller may or may not allow the tractive effort level to be set explicitly, and if so the proportion of the total tractive effort available may be either continuous or have discrete values (termed notches). Generally, electric locomotives are likely to have continuous control of tractive effort, and diesel trains notched controllers, although electric multiple units may not necessarily be able to control tractive effort directly. The Tyne and Wear Metro is one such example, and is detailed in Section 3. There are many exceptions to this generalisation however, and any investigation requires specific knowledge of the train in question.

## ***2.2 Cruising***

Once the train speed has reached line speed (the speed limit for that particular section), the driver can use a combination of traction, free running or braking to hold the speed close to this limit. This operational phase may also be referred to as speed holding or free running; in this paper however free running is defined as the absence of tractive or braking effort.

A model for cruising is described by Lukaszewicz (2001), where a limit below and above the nominal line speed is proposed for a change of the driver's action. Above the upper limit the brakes are applied, and below the lower limit power is applied, until

the train speed returns to nominal line speed; at this point the driver returns to free running. The upper limit was slightly above the line speed in Lukaszewicz's results. A similar approach is described by Kulworawanichpong (2003) and termed hysteresis control, albeit with either maximum tractive effort or maximum braking effort demanded and no free running between these extremes. An alternative strategy (proportional control) is also described, where the level of tractive or braking effort chosen is proportional to the difference between the actual and target speed.

Both hysteresis and proportional control are possible options for driving strategy, although the use of proportional control may be limited by the design of the driver's controller and its relationship to the possible levels of tractive and braking effort. Note that there may also be a difference in energy consumption between the two control strategies, depending on the relative efficiency of the traction equipment at different power levels and speeds, but it requires detailed modelling of the particular train under consideration to determine whether this effect is significant.

### ***2.3 Coasting***

In this paper, coasting refers to an extended period of free running that makes up an operational phase in its own right, rather than brief periods of free running during the cruising phase. The use of coasting instead of cruising is intended to reduce the overall energy consumption, but at the expense of an increase in journey time between scheduled stops.

A reduction in either the maximum speed or the acceleration rate is another way of achieving this goal however, and the three principal areas where energy is lost in the motion of a train should be considered to compare these strategies:



- Resistance to motion, where the energy loss is a quadratic function of speed.  
This can be minimised by reducing the maximum speed of the train.
- Heat generated by the brakes, governed by the train's speed when the brakes are applied. This brake entry speed can be reduced by coasting immediately before a brake application is made.
- Traction system efficiency, which has already been noted above as varying under full and part load conditions across the speed range. Likewise, power supply system losses for electric trains are a function of current drawn squared; the tractive effort (and hence acceleration) is approximately proportional to this current, so a reduction in acceleration rate reduces the supply system losses.

The relative importance of each of these three factors, and hence most effective strategy for reducing energy consumption, will depend on the characteristics of the train and route in question. Reducing maximum speed or brake entry speed are however generally more effective at reducing energy consumption in most situations; the primary purpose of reducing the acceleration rate is usually to limit the maximum current drawn from the supply system if several trains are accelerating simultaneously.

A further implication of the above is that reducing the use of braking will also reduce energy consumption, for example by coasting on the approach to a downhill gradient that would otherwise require braking to prevent the line speed being exceeded. This can also be applied to stops at signals (when there is disruption to the timetabled schedule) if a driver advisory system is in place that alerts the driver to adverse signal aspects before the point at which braking is required. There are further potential benefits if this is integrated into a traffic management system that can anticipate when the signal is likely to change to a less restrictive aspect: although a train may be further from the signal, it is still moving and may clear the next signal section sooner than if it had to

restart from rest. The potential benefits from this situation were investigated by Albrecht (2009). However, reducing speed earlier than necessary may cause further conflicts behind the train in question, and so the effect on other trains must be taken into account by the overall traffic management system in deciding whether trains should brake to a stop, or use a combination of coasting and/or braking to approach a signal at lower speed.

When regenerative braking is in use, the amount of energy that can be recovered depends on the receptivity of the power supply network, which is a function of the loads on the network (typically other trains accelerating) at that instant in time. A second application of a traffic management and driver advisory system is therefore to aim to synchronise the acceleration and braking phases of nearby trains to maximise the network's receptivity to regenerated energy. This will also affect the choice of strategy to reduce energy consumption.

## ***2.4 Braking***

When required to decelerate to a lower line speed, or stop at a signal or station, there are two distinct braking strategies for the train. The first strategy is to aim for a nominally constant braking effort across the speed range, and driver's brake controllers are generally designed to achieve this for a particular setting. As with traction controllers, there may be defined notches or continuous variation of this effort. The four limits on traction highlighted in Section 2.1 (adhesion, motor temperature, in-train forces and jerk levels) are equally applicable to braking. The consequences of wheel slide in braking are more severe than for wheel spin in traction if the available adhesion is exceeded however, as it is more damaging to the wheelset, and there is also the potential for overrunning stations or signals. The assumed design adhesion level is therefore lower for braking – around 9% for a full service brake application in Great Britain (*Adhesion*

*Working Group, 2004).*

For trains with dynamic braking, the second strategy aims to minimise the use of the friction brake to reduce wear, and also reduce the overall energy consumption of the train if regenerative braking is possible. Friction brakes are usually rated for the maximum speed of a train, and can therefore provide a nominally constant force across the speed range. The braking force from dynamic brakes is typically limited by the power of the traction system however, and braking effort reduces at higher speeds in the same way as tractive effort.

Dynamic braking may have a separate controller, or be combined with the traction and/or friction brake controller; this in turn requires automatic blending of dynamic brake effort with the friction brake to obtain a nominally constant force overall. Locomotives may also have an independent friction brake that acts on the locomotive wheels only.

For the acceleration phase, the start location and speed is known, and the transition to a different operating phase occurs at a defined speed - the location is not important. For the braking phase, the final speed and location are both important, but the speed and location for the transition from another phase is not fixed, and varies according to conditions such as wind speed and direction, as well as the driver's perception. Therefore, even if the driving strategy is for a nominally constant brake force, there are likely to be adjustments to the brake rate during deceleration to reach the target speed (or stop) at the correct location.

### **3. Model case study – the Tyne and Wear Metro**

The Tyne and Wear Metro is a light rail system centred on Newcastle upon Tyne in the north-east of England. The first 54 km of the network were opened progressively from 1980, using a combination of existing heavy-rail alignments converted to Metro use,

new tunnels through the centre of Newcastle, and a new bridge across the river Tyne. The network was subsequently extended to Newcastle International Airport in 1991 and South Hylton in 2002, the latter extension sharing tracks with heavy rail services between Pelaw and Sunderland. Howard (1976) and Mackay (1999) provide a more detailed description of the genesis of the system.

The original rolling stock remains in service today: 90 twin-section articulated Metrocars, built by Metro-Cammell with electrical equipment by GEC Traction and bogies/articulation design by Düwag. The fleet was refurbished between 1995 and 2000, and is currently undergoing life extension work to run until the mid-2020s. The trains are fed with 1500 V DC from overhead wires, with a 185 kW series-wound DC monomotor on each outer bogie, resistance-controlled by an air/oil camshaft. Braking is a combination of rheostatic and spring applied/air released friction brakes; there are also emergency track brakes.

The theory that underpins the design of resistance-controlled DC electrical multiple units was established over a century ago, and is comprehensively described by Dover (1917). The Metrocar camshafts have thirteen resistance steps for traction, the two motors are connected in series only, and there are four camshaft steps for field weakening. The resistance step switching is automatic based on motor current, and the driver's controller has three positions:

- Shunt - the line contactors are closed, but all series resistors remain in the circuit
- Full field - all series resistors are progressively switched out of the circuit
- Weak field - the field weakening resistors are progressively connected to the circuit

The above arrangement means that the driver cannot set the tractive effort directly; the

choice of whether to step through the series resistances and field weakening resistances is controlled instead. There are however three possible settings for the motor current at which the camshaft resistance steps are made (and hence some control over the tractive effort level is provided): these are for low adhesion conditions, normal operation and for hauling a second Metrocar that has suffered a traction system failure.

The braking is normally provided by a mixture of friction and rheostatic braking. There are twelve resistance steps for braking, and the motors are cross-connected in parallel with no field weakening. The friction brakes on the unpowered bogie are always used, and the friction brakes on the motor bogies are automatically blended with the rheostatic brake at low speeds, as well as for the short time that it takes for the rheostatic brake to take effect after braking effort is initially demanded. There are four normal positions for the brake controller that provide different levels of braking effort, named steps 1 to 3 and full service braking. These notches control the air pressure in the friction braking system and the values of motor current at which the resistor transition steps are made. There are also two emergency notches that use either friction brakes only or friction and track brakes. The values of motor current for the resistor transition steps and the air brake controller are linked to the load-weighing system in the air suspension, to increase the tractive and braking effort when a greater mass of passengers is being carried.

To put the above discussion in context for the purposes of this paper, Figure 1 illustrates the overall tractive/ braking effort-speed curves, showing each controller notch: weak field, full field, shunt, off, braking steps 1-3 and full service brake.

## 4. Model methodology

### 4.1. Control system

To investigate the variation in driving profiles, a model was developed in Microsoft Excel to generate an estimated speed profile for individual station to station runs (to compare against measured data), using the tractive effort-speed curves in Figure 1 and a driving strategy based on the information in Sections 2 and 3.

The driving strategy model specifies the driver's controller notch by comparing the train's actual speed with the target speed at the train's current location. During the acceleration phase, maximum tractive effort up to the target speed ( $V_t$ ) is demanded; the model proposed by Lukaszewicz (2001) for free running between this upper speed limit and a lower speed limit ( $V_c$ ) is then followed for the cruising phase. Where there is a transition from accelerating/cruising to the coasting phase, the lower limit  $V_c$  at which power is applied is decreased further. Above the line speed limit ( $V_o$ ), the brake notches are applied in turn if speed continues to increase ( $V_{b1}$  to  $V_{bFS}$ ). This is in the same manner as the proportional control proposed by Kulworawanichpong (2003), although modified to account for a notched rather than continuous brake controller, and including a degree of hysteresis between brake notches to prevent excessive hunting. The behaviour described above is illustrated diagrammatically in Figure 2.

The full target speed profile ( $V_t$ ) at all points is generated from the line speed for the relevant track section, with the location of braking points for the destination station and line speed limit reductions calculated for a constant deceleration rate ( $D$  - an input parameter to the model) and the gradients on that section of track. The driving strategy model is then applied to this speed profile, with further input parameters describing the relationships between  $V_o$ ,  $V_t$  and the other speed limits. An illustrative example set of

curves generated are shown in Figure 3 for a run between two stations 1210 m apart, with a reduction in line speed at 760 m.

#### ***4.2. Traction simulation***

To obtain a speed profile, the model recalculates the resultant force acting on the train every 0.1 s. The instantaneous tractive/braking effort is derived from the train's speed and location with reference to Figures 1-3, the rolling and aerodynamic resistance to motion is calculated from the speed (using train resistance data from tests when the Metro was constructed), and the force due to gravity calculated in accordance with the gradient at the train's location. The resulting acceleration and the train speed are assumed constant over the 0.1 s time step to calculate a new speed and position, and this calculation is repeated until the end location is reached to give the overall speed profile. The 0.1 s value for time step was chosen to be the largest that did not result in significant differences in the results to using other time step values, in order to balance computation time against errors introduced from the use of a discrete time step.

#### ***4.3. Calibration***

Four pairs of stations, each illustrating a slightly different situation, were chosen to validate the proposed model and investigate the variation in real driving profiles. Ilford Road to South Gosforth and Felling to Gateshead Stadium both have reasonably consistent gradients and constant line speed limit, although the latter is approximately double the length. West Jesmond to Jesmond involves a reduction in line speed limit between the two stations, and Central Station to Gateshead has significant changes in gradients (both uphill and downhill). Measured speed profile data, sampled approximately every second, was obtained from energy meters fitted to two Metrocars (units 4067 and 4080) for several journeys in October 2012 between the station pairs

chosen. The data is from different days, and times of day; it is therefore reasonable to assume that there are several different drivers in the sample.

Given the scope of this investigation, only the target speed for the acceleration phase ( $V_t$ ) and the deceleration rate ( $D$ ) were calibrated to fit the real data, the control parameters (that set  $V_c$  and  $V_{b1}$  to  $V_{bFS}$ ) were set as constants for all runs in accordance with Lukaszewicz's results as a first estimate, and checked against the measured data to ensure a reasonable fit. The calibration process was as follows:

- The speed profile data from the energy meters and the results of the simulation model with the current input parameters were plotted on the same set of axes as a visual reference.
- The difference in journey time (from the moment the train departs the first station until the moment it stops at the second, dwell time is not relevant here) between the real and simulated profiles was calculated.
- Given the simulation model time step and the time intervals of the measured data do not match (0.1 s compared to  $\sim 1$  s; see paragraphs above), the model speed at the time corresponding to each measured data point was calculated by linear interpolation from the two adjacent simulated values.
- The difference between the measured and simulated speed for each measured data point was calculated, and the root mean squared error calculated using all of the deviations from the entire journey.
- The values of the target speed ( $V_t$ ) and deceleration rate ( $D$ ) were varied over many iterations in order to minimise both the difference in journey time and root mean squared error for the difference in the speed profile. This gives the values of the parameters that characterise the run under investigation.



For all of the station pairs considered here, there was no cruising, the operational phase changed to coasting as soon as the target speed was reached.

## 5. Results

A total of 24 different runs across the four station pairs were analysed, with the input parameters for the model being recalibrated for each individual run. An example for each station pair is shown in Figure 4 as an illustration of the results; the profile created by the model is the continuous line, and the markers are the measured data points. Note that the runs illustrated in Figure 4 for each station pair were arbitrarily chosen as reasonably representative of the graphs for each set, all 24 runs are equally valid for analysis and conclusions.

As described in Section 4, this investigation only considered the variation in target speed ( $V_t$ ) and the deceleration rate ( $D$ ) to calibrate the model for each run analysed. The values for these input parameters that gave the best fit for each of the individual 24 runs analysed are given in Table 1, along with the mean and standard deviation for each route and also the input parameter overall. The bold values correspond to the runs illustrated in Figure 4.

An additional application for the model is to set the target deceleration rate  $D$  to the maximum that the Metrocars can achieve ( $1.15 \text{ m s}^{-2}$ ) and the target speed  $V_t$  to 100% of line speed  $V_o$ , with no coasting ( $V_c = V_t$ ), and hence derive an approximation of the idealised minimum time profile for each station pair. Table 2 shows the measured running time for each of the 24 runs (and their mean), alongside the minimum time calculated.

The range in the running times for given station pairs is around 10-13% of the mean; there is less of a pattern in the difference between the mean measured running

time and idealised minimum running time however. This illustrates directly the differences between real-life conditions and the idealised minimum time profile.

## **6. Discussion**

### ***6.1. Comparison of modelled and real-life driving profiles***

It can be seen from the examples illustrated in Figure 4 that the model does reflect the measured profiles; there are however some differences that should be analysed to determine the level of accuracy achieved.

The most noticeable deviations from the model speed profile occur during braking, partly due to a difference in driver behaviour; the reasons are investigated in Section 6.2. The deviations during the acceleration phase, although noticeable, are less significant: unlike the braking phase, the broad trends (and hence shape of the speed profile) in the modelled and measured profiles are generally a close match. The reasons are therefore more likely to be due to uncertainties in the model rather than fundamental differences in driver behaviour, and these are investigated in Sections 6.3 and 6.4. The coasting phase shows a good match between the two profiles.

The Central Station – Gateshead section has some anomalous results by comparison with the others, and these are also discussed below.

### ***6.2. Driver behaviour***

The primary reason for the noticeable differences in speed profile during braking is that the model does not fully account for errors in the driver's perception of the correct braking point and subsequent corrections for different speeds and conditions (as detailed in Section 2.4.). These deviations can be most easily observed in the West Jesmond – Jesmond profiles in Figure 4. They are partly mitigated in the model by a lower

(constant) target deceleration rate so that the overall journey time is correct.

Another feature of the driver behaviour can be observed in Figure 4 and Table 1: for the Central Station to Gateshead pair the target deceleration rate is much higher than the others pairs, generally close to step 2 or step 3 braking rather than step 1. The measured data was from October, which is leaf fall season, and drivers are instructed to brake more gently at this time of year to reduce the risk of wheel slide. The approach to Gateshead is underground however, and therefore not affected by leaf fall. Comparison with data from another time of year would be required to determine whether this is the case; if so then all station pairs would be expected to display the high deceleration rate.

### ***6.3. Uncertainty in simulation model***

The curves illustrated in Figure 1 assume a crush loaded train, 98% transmission efficiency, part-worn wheels (710 mm diameter) and 1350 V line voltage. The effects of passenger load on acceleration are minimised by the load-weighing equipment below the full crush load, and the errors in the gearbox transmission efficiency estimate are negligible. However, the energy meter data showed a typical variation in line voltage of 1300 to 1600 V; increases in line voltage will scale the curves in Figure 1 linearly in the positive  $x$  (speed) direction, corresponding to increase in power. The wheel diameter can vary from 740 mm (new) to 660 mm (fully worn); a larger wheel diameter will scale the curves in the positive  $x$  (speed) and negative  $y$  (force) directions, with nominal power remaining the same. In addition to these uncertainties with known ranges, the effect of manufacturing tolerances and subsequent drift in performance of components that have been in service for 30 years should not be ignored: variations of the order of 10% in the performance between different trains in the same fleet are not unusual. Further second order effects include the time delay associated with camshaft switching and pneumatic brake applications, which will effectively limit the rate of change of

tractive and braking effort. For the Metrocar, these will act over a shorter time than the measured data time interval. The accuracy of the speed measurement of the energy meters used to collect the data is around 4%.

A separate effect that cannot be controlled is that of the wind, which will change the aerodynamic resistance of the train, depending on the wind direction and magnitude, although this in turn will be affected by lineside terrain and structures. For the dates in October 2012 in which data was collected, the wind typically varied between 0 and 15 km h<sup>-1</sup>.

Although it was not possible to reduce the differences between journey time and speed profile to zero in the calibration process, the remaining errors were several orders of magnitude smaller than the uncertainty in the physical model, and were therefore considered negligible. Likewise, the errors resulting from the discrete simulation time step and interpolation to find the simulated speed at each instant corresponding to a measured data point were also small enough to be neglected.

#### ***6.4. Model accuracy***

The factors identified in Section 6.3. will have different effects at different speeds (line voltage also depends on other trains in the vicinity), and to illustrate their effects Figure 5 shows possible variation for the simulated speed profile during the acceleration phase of the Ilford Road – South Gosforth station pair if the full ranges of the above parameters are considered. An extended range that also includes a 10% allowance for variation in train performance due to manufacturing tolerances and component deterioration is also shown.

These are compared to the measured data shown in Figure 4, and it can be seen that this measured data falls within the range predicted purely from measurable quantities, without taking unpredictable manufacturing tolerances into account. The

uncertainty is dominated at low speeds by the  $\sim 1$  s sample time of the energy meter, with other factors having a greater effect at higher speeds. It should be noted that analysis of the precise reasons for the deviation of the simulation model data from the measured data cannot be determined with any confidence without more accurate experimental data, the only conclusion to draw from the above analysis is that the model appears a reasonable fit to the measured data.

### ***6.5. Other factors***

The effects of two other potential sources of error can also be seen in the Central Station – Gateshead profile specifically. The gradient profile between these stations includes a change from 1 in 47 up to 1 in 43 down; this change will not be instantaneous but smoothed by a vertical transition curve over a distance of around 100 m, which results in a smoother profile in the external forces acting on the train. Parts of this section are also in single track tunnels, which will significantly increase aerodynamic resistance. In addition to changes in the driver behaviour discussed in Section 6.2. above, this may also be a contributing factor to the higher deceleration rates seen for this station pair.

## **7. Conclusions**

The model developed and described in this paper provides a good first order approximation to measured railway driving profiles, well within the range of uncertainty typically found in traction modelling of this nature.

The model was built by considering the design and control of the train as the starting point – this has allowed the variation in driver behaviour in operating a particular design of train (and its controls) to be described explicitly by the model.

Although the Tyne and Wear Metro was used as the case study, the methodology can be

applied to other railway systems by redefining the tractive effort characteristics and driving strategy (Figures 1 and 2 respectively).

The variation (expressed as a mean, standard deviation and extension to running time from the minimum) across many runs of the model input parameters illustrates quantitatively the variation in real measured driving profiles.

In addition, a further output of the model is the position of the driver's controller. The state of the train's traction system and the variation in the driving profile are both useful inputs to more complex simulations that model the interaction of many trains across a network. These results can therefore be applied in the wider railway context to improve predicted train behaviour, with significant potential benefits for studies into timetabling, traffic management and optimisation of energy consumption.

The area in which there is the most potential for further work and development is modelling the braking phase in more detail; this showed the greatest deviation between the model and the measured data, which is principally due to variation in drivers' perceptions of the correct braking point for different speeds and weather conditions. In addition, accounting for vertical transition curves in the track layout and the increase in resistance to motion when running in tunnels would also improve the accuracy of the model for certain station to station pairs.

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Table 1. Full results for the two input parameters used to calibrate the model

		Individual runs						$\mu$		$\sigma$	
Target maximum speed (as a proportion of line speed) $V_t/V_o$	Ilford Road - South Gosforth	<b>0.85</b>	0.67	0.8	0.71	0.95	0.92	0.82	0.87	0.10	0.086
	West Jesmond - Jesmond	0.86	<b>0.82</b>	0.87	0.96	0.98	0.73	0.87		0.084	
	Central Station - Gateshead	0.9	0.85	0.87	0.8	0.82	<b>0.93</b>	0.86		0.045	
	Felling - Gateshead Stadium	0.98	0.79	0.88	0.89	<b>0.96</b>	0.97	0.91		0.067	
Target deceleration value ( $\text{m s}^{-2}$ ) $D$	Ilford Road - South Gosforth	<b>0.54</b>	0.39	0.37	0.39	0.34	0.41	0.41	0.58	0.063	0.23
	West Jesmond - Jesmond	0.45	<b>0.35</b>	0.48	0.45	0.47	0.79	0.50		0.14	
	Central Station - Gateshead	0.63	0.87	1.14	1.06	0.83	<b>0.96</b>	0.92		0.17	
	Felling - Gateshead Stadium	0.56	0.51	0.45	0.45	<b>0.58</b>	0.53	0.51		0.050	



Table 2. Variation in total running times

		Individual runs						$\mu$	Minimum
Running time (s)	Ilford Road - South Gosforth	<b>59.2</b>	66.5	65.6	65.5	66.7	63.2	<i>64.5</i>	<i>50.9</i>
	West Jesmond - Jesmond	92.5	<b>97.7</b>	91.5	89.2	88.0	93.7	<i>92.1</i>	<i>85.1</i>
	Central Station - Gateshead	106.5	102.0	98.0	105.0	105.0	<b>94.8</b>	<i>101.9</i>	<i>86.6</i>
	Felling - Gateshead Stadium	82.8	93.4	91.4	90.4	<b>82.5</b>	84.6	<i>87.5</i>	<i>73.2</i>

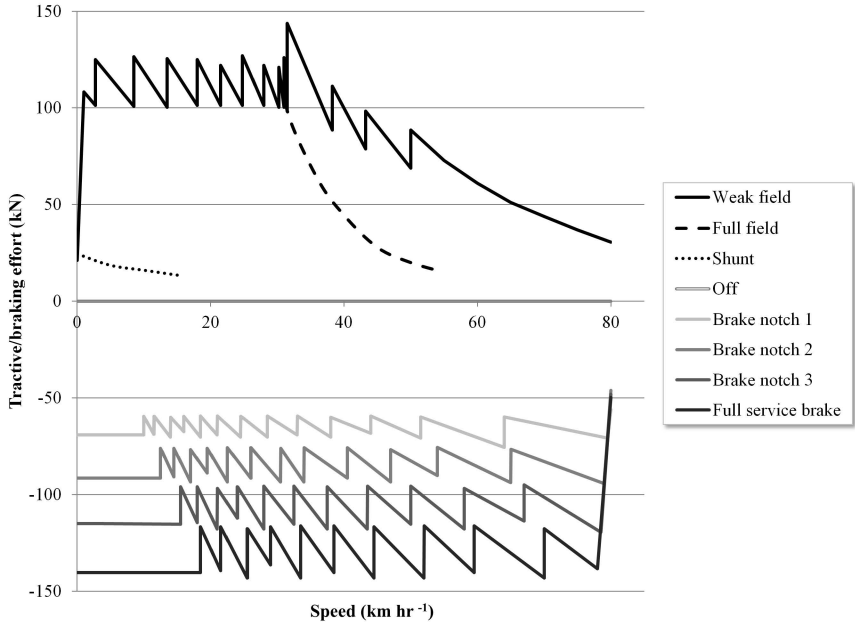
Figure 1. Tractive effort curves for Tyne and Wear Metrocar

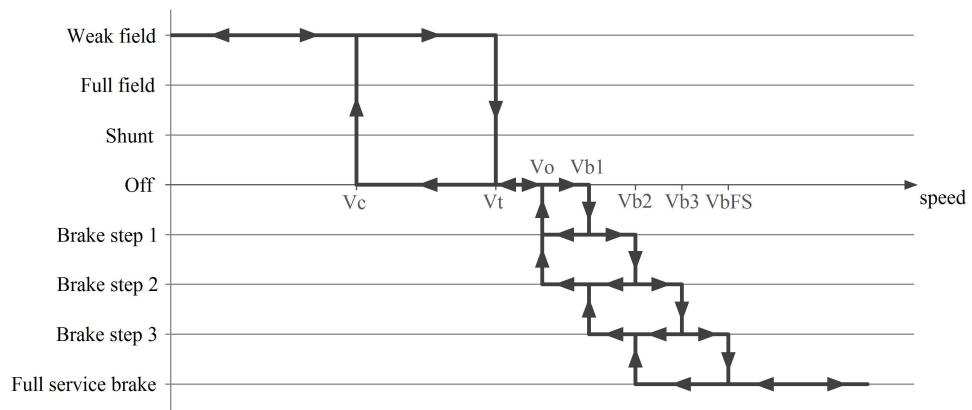
Figure 2. Driving strategy model

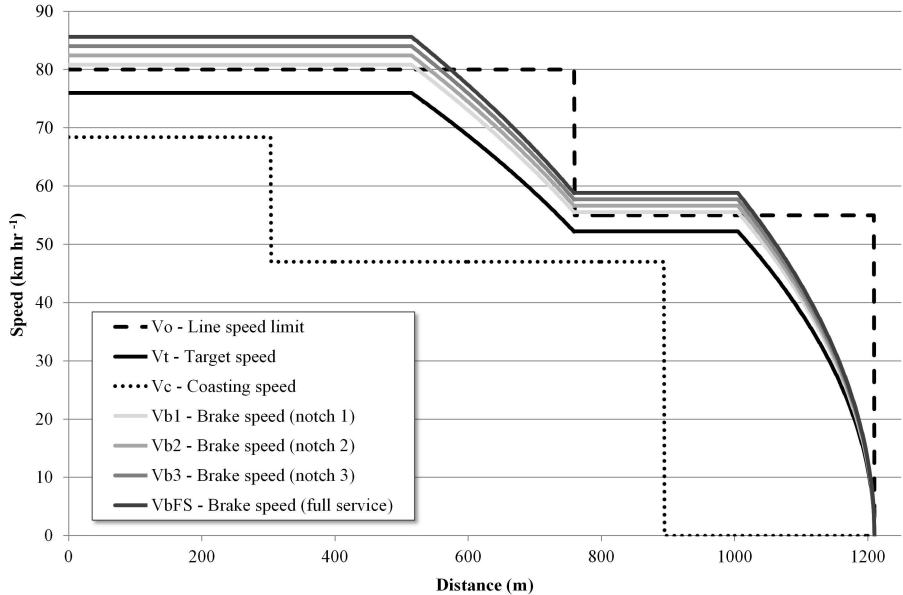
Figure 3. Example speed profile curves

Figure 4. Example comparison between the model and measured speed profiles

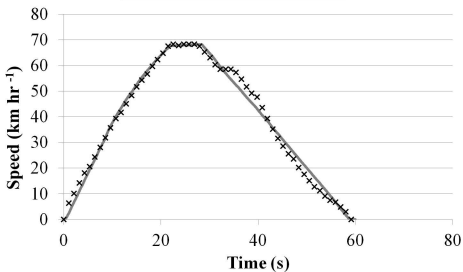
Figure 5. Simulation uncertainty range



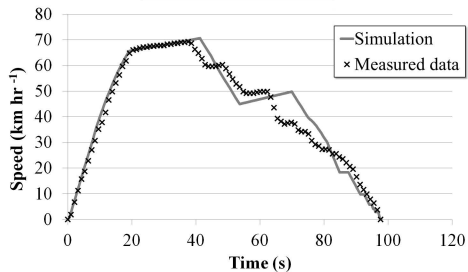




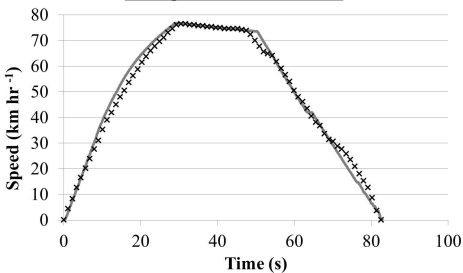
**Ilford Road - South Gosforth**



**West Jesmond - Jesmond**



**Felling - Gateshead Stadium**



**Central Station - Gateshead**

